$\boxed{\text{Neutrino Physics at Fermilab}}$

University of Rochester
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Outline

1. Neutrinos? At Particle Accelerators? Why?
2. Neutrino as Probe
3. Neutrino as Neutrino
4. Future Neutrino Endeavors

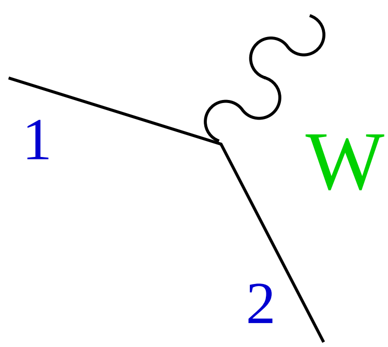
Neutrinos are spin-1/2 particles, with no electric charge, no strong interactions and little or no mass

Where do Neutrinos Fit in the Standard Model?

Leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

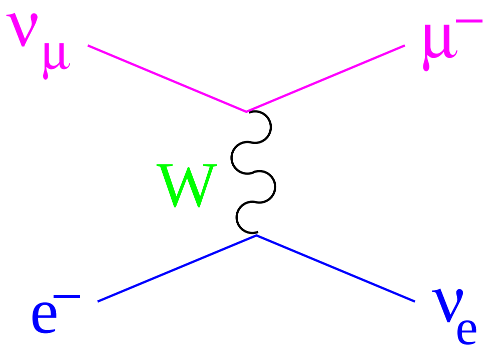
Quarks: $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

Force	Carrier	Participants
Strong	gluons	quarks, gluons
Electromagnetic	photon	charged particles
Weak	$W^\pm$, Z^0	all, including neutrinos!



- The Charge-Carrying Weak force connects members within doublets above.
- In the quark sector, it can connect *different* families of doublets, but this has not been observed in the lepton sector.

The Weak force is "weak" because it is mediated by a massive particle



$$\frac{d\sigma}{dq^2} = \frac{2}{\pi}\left(\frac{g_W^2}{q^2 + {M_W}^2}\right)^2$$

$$q^2_{\text{max}} = 2m_e E_\nu$$

$$\Rightarrow\ \sigma \propto E_\nu$$

And σ/E_ν is tiny!

Total interaction cross-sections for 100 GeV particles onto a target are:

- $\sim 10^{-40}\text{cm}^2$ for neutrino-electron scattering
- $\sim 10^{-36}\text{cm}^2$ for neutrino-nucleon scattering
- cf: $\sim 10^{-25}\text{cm}^2$ cross-section for *pp* scattering

A 100 GeV neutrino has a mean free path in steel of 3×10^9 meters (10 light seconds)

If you're going to observe neutrino interactions...
... you need a lot of neutrinos and a lot of detector

Some Highlights from the History of the Neutrino

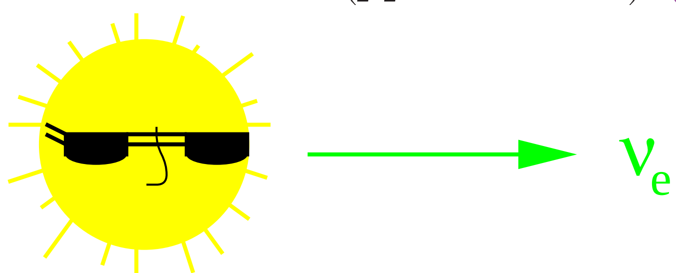
1930	Pauli Postulates ν existence	$n \to p + e^- + ???$ Is Energy Conserved?
1953 Nobel 1995	ν Interactions Observed Reines & Cowan	$\overline{\nu} + p \to n + e^+$
1962 Nobel 1988	ν_μ Observed Lederman, Schwartz, Steinberger	$\nu_\mu + N \to \mu^- + X$
1973	Neutral Current ν Interactions Observed Gargamelle	$\nu + N \to \nu + X$
1989	3 light ν families! LEP Experiments	$Z \to \nu\overline{\nu}$

Neutrino Physics is not a field whose rewards come quickly or easily...

Where are neutrinos found in nature?

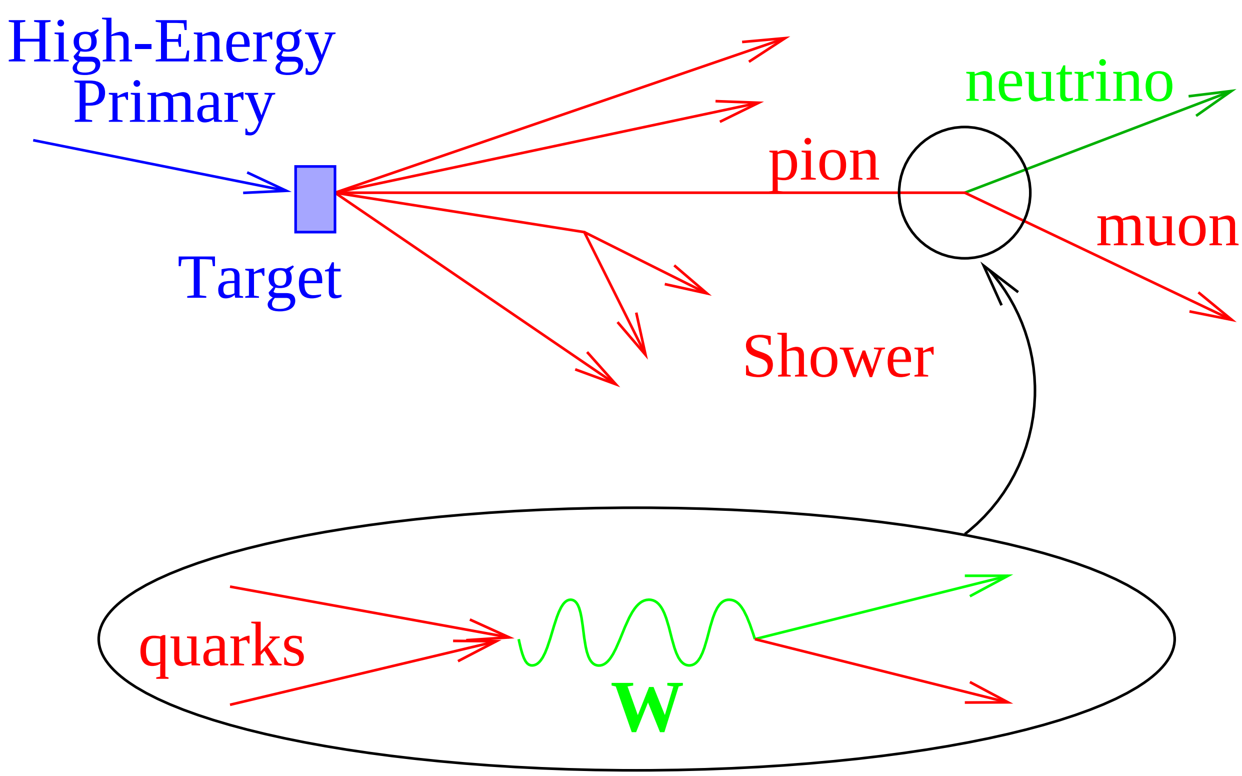
...anywhere weak interactions can produce them

- Relic neutrinos from early universe ($\sim 300/\mathrm{cc}$, $0.2\,\mathrm{meV}$)
- Radioactive decays, fission reactors ($n \to pe^-\overline{\nu}_e$) or fusion reactors ($pp \to de^+\nu_e$) ($\sim 1\mathrm{MeV}$)



($10^{11}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$)

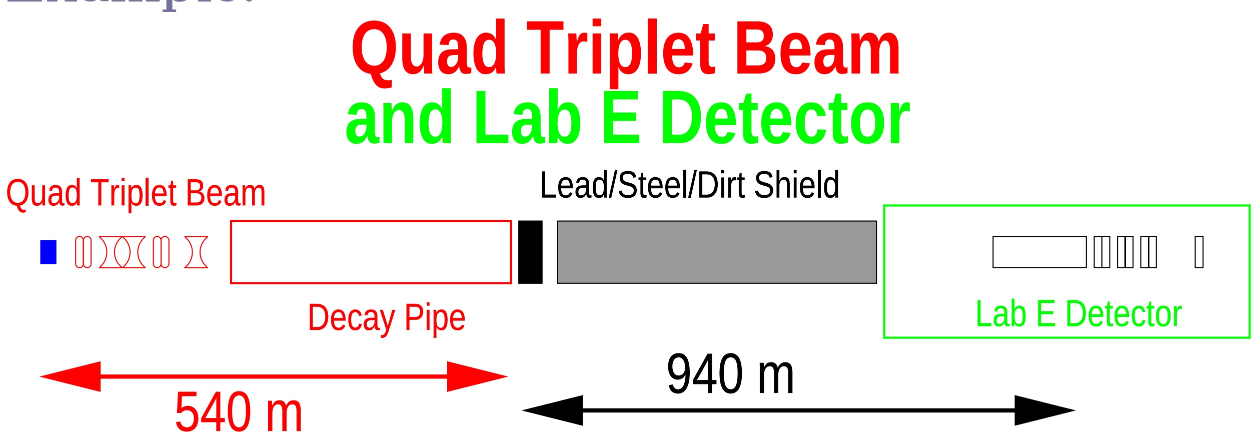
- Products of high-energy interactions



To make a "neutrino beam" at an accelerator...

1. Take the highest energy particles you can make
2. Hit a target and produce unstable, weakly-decaying particles
3. Allow those particles to decay into neutrinos

Example:



10^{13} protons (800 GeV)

2×10^{12} pions and kaons

3×10^{10} neutrinos (20-400 GeV)

Basic Requirements for a Detector to Observe Neutrino-Nucleon Scattering:

- Transverse size comparable to the beam size
- Sufficient length to ensure a reasonable number of neutrino interactions
- Active detector material throughout target

The Heisenberg Insolvency Principle
for Neutrino Targets?

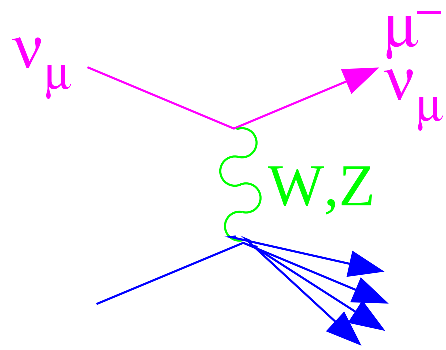
$$(\text{Mass}) \times (\text{Resolution}) \lesssim \text{constant}(\$\$\$)$$

Different choices in detector design...
... lead to different physics capabilities

$\boxed{1}$ Maximize Mass and live with a coarsely instrumented detector.

Example: CCFR Neutrino Detector

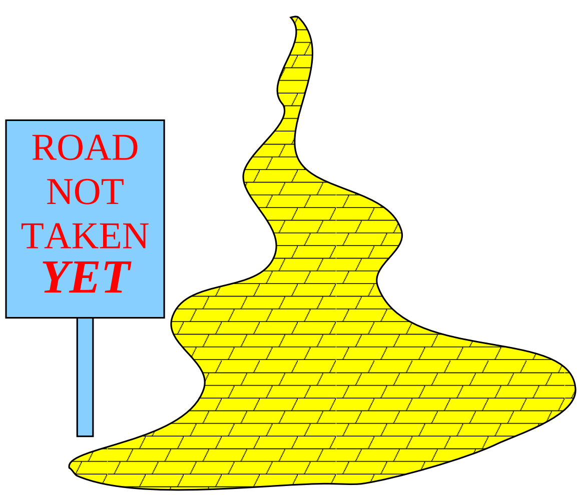
- 690 tons, detectors spaced every 4 inches of steel
- High statistics, but only particle that can be identified is the muon.

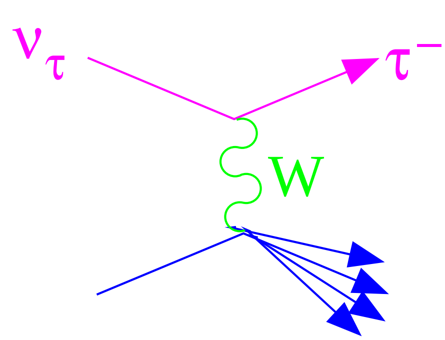


$\boxed{2}$ Small, but fully-active fine-grained detector.

Example: CHORUS Neutrino Detector

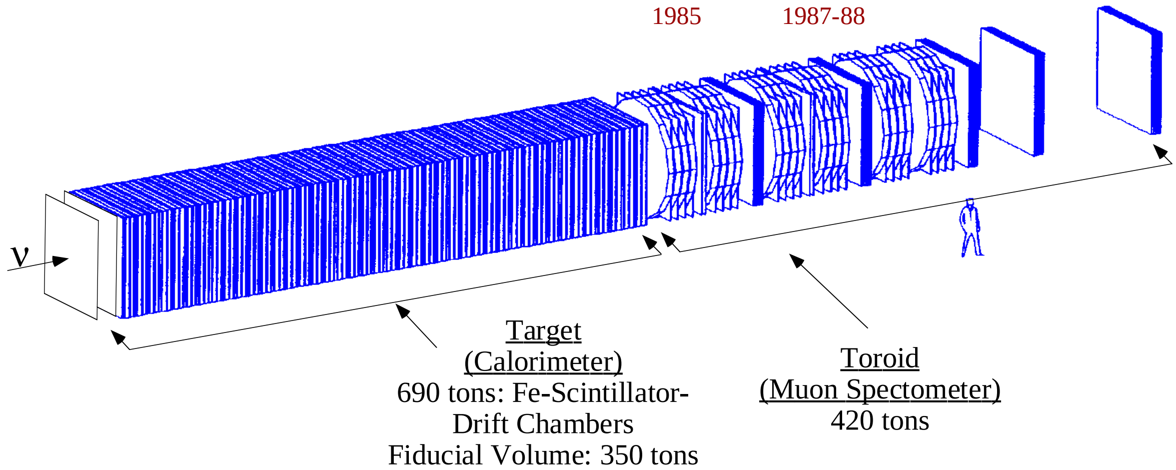
- 1 ton emulsion target
- Can identify short ($> 20\ \mu$m) tracks from unstable τ leptons.





CCFR (Columbia-Chicago-Fermilab-Rochester)

LAB-E Detector - Fermilab E744 and E770



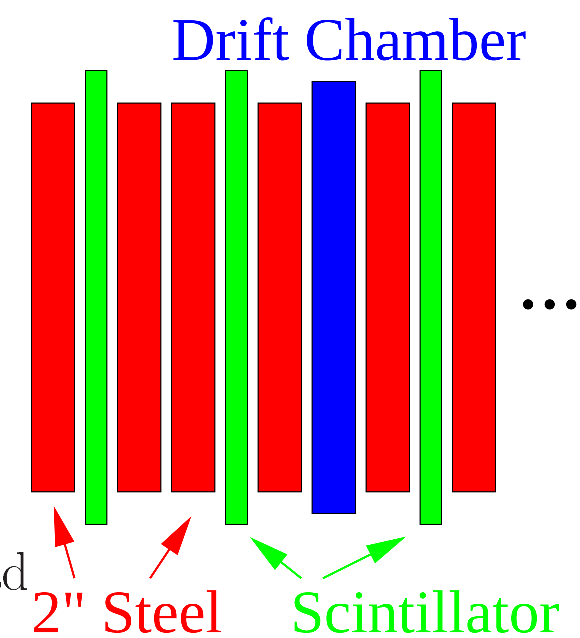
Target

- Measures energy of hadronic system

$$\frac{\sigma_E}{E} \approx \frac{0.9}{\sqrt{E\ (\mathrm{GeV})}}$$

- Tracks final state muon

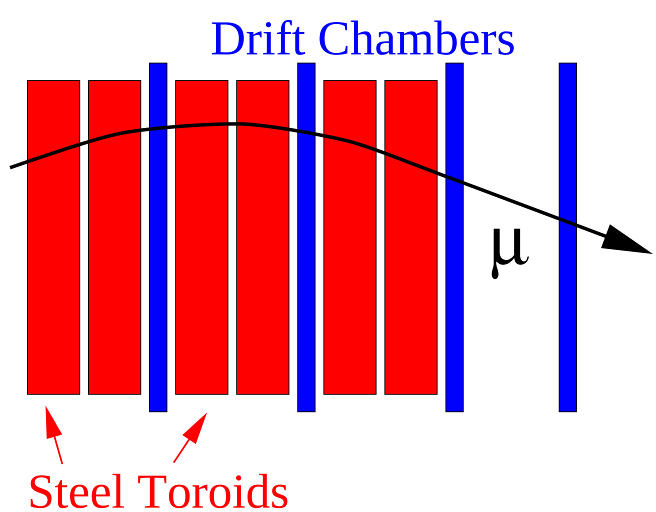
$$\sigma_\theta \sim \left(0.3 + \frac{70\ \mathrm{GeV}}{p}\right)\ \mathrm{mrad}$$

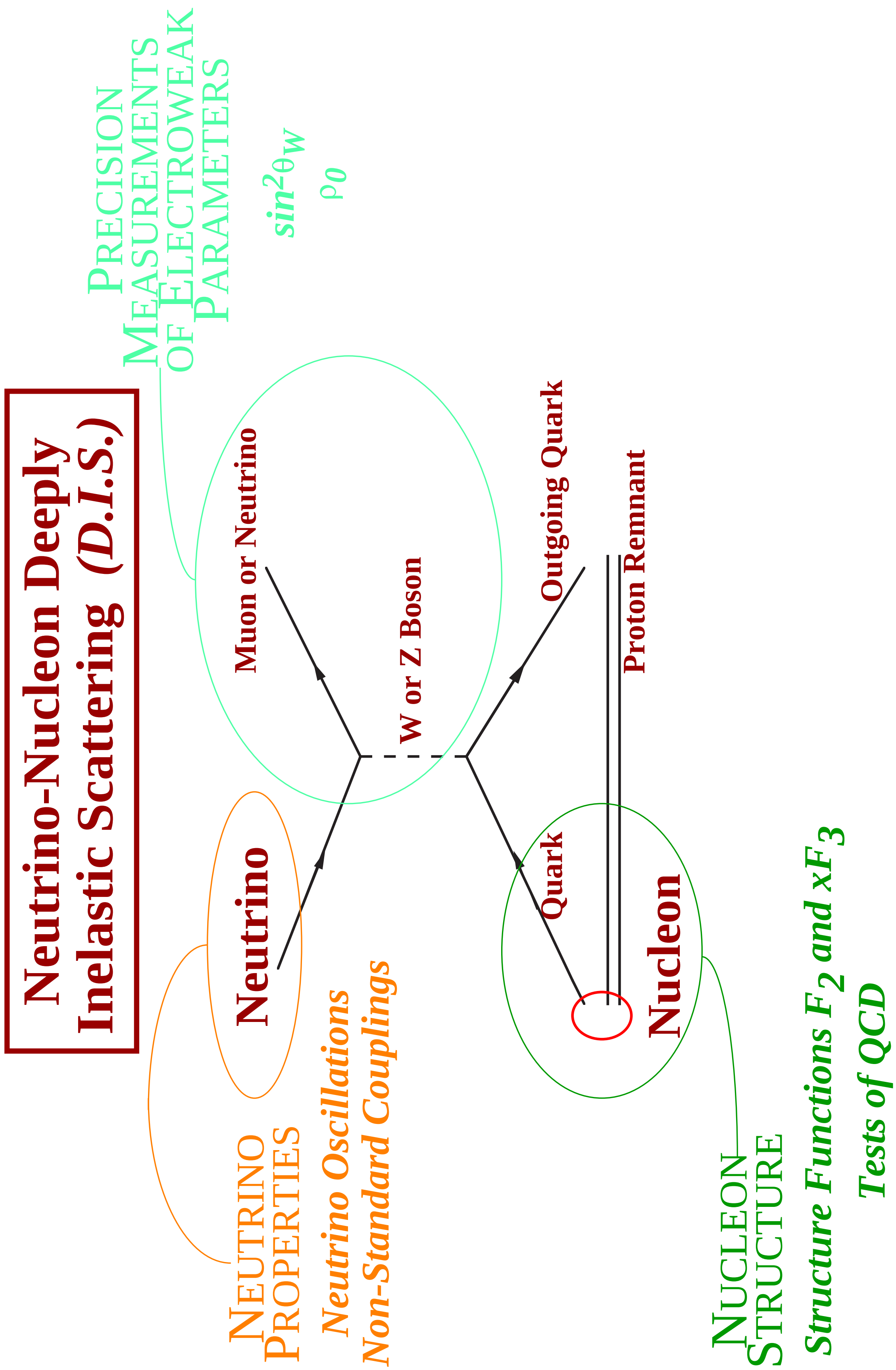


Toroid

- Magnetic field bends muon
- Curvature measures muon momentum

$$\frac{\sigma_p}{p} \approx 0.11$$



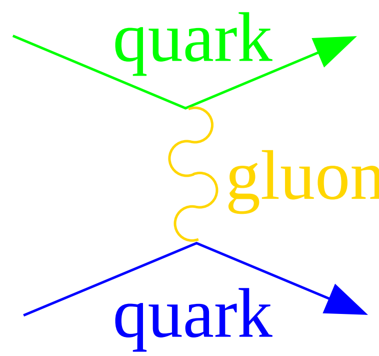

Neutrino-Nucleon Deeply Inelastic Scattering (D.I.S.)
Precision Measurements of Electroweak Parameters
$sin^2\theta_W$
ρ_0
Muon or Neutrino
W or Z Boson
Outgoing Quark
Proton Remnant
Neutrino
Quark
Nucleon
Neutrino Properties
Neutrino Oscillations
Non-Standard Couplings
Nucleon Structure
Structure Functions F_2 and xF_3
Tests of QCD

Studies of QCD with Neutrinos

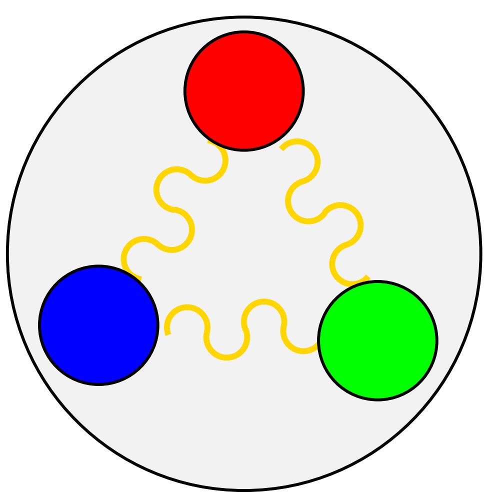
Quantum Chromodynamics is...

... the theory of Strong Interactions

In QCD, Quark-Quark Interactions are mediated by the Gluon



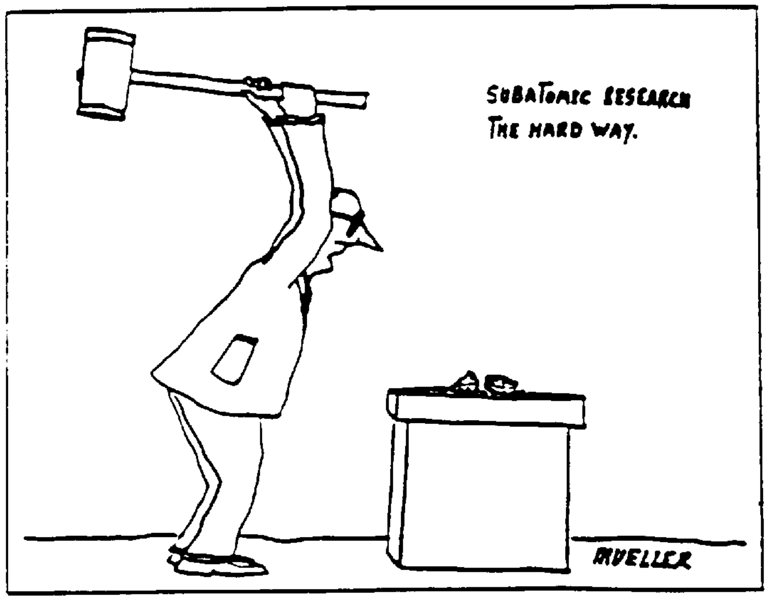
Proton in QCD



Quarks bound by gluons

What a proton looks like...

...depends on your probe

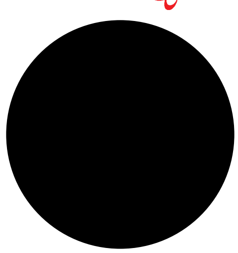


Higher momentum transferred (Q^2)

means small wavelength (DeBroglie, $\lambda \sim \frac{1}{\sqrt{Q^2}}$)

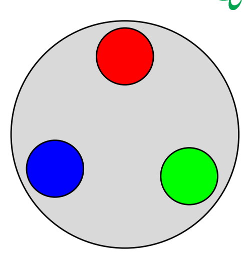
and higher resolution.

Low Q^2



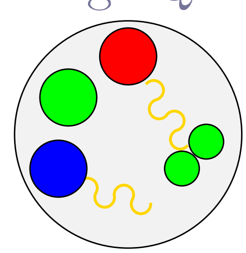
No structure

Moderate Q^2



Valence Quarks

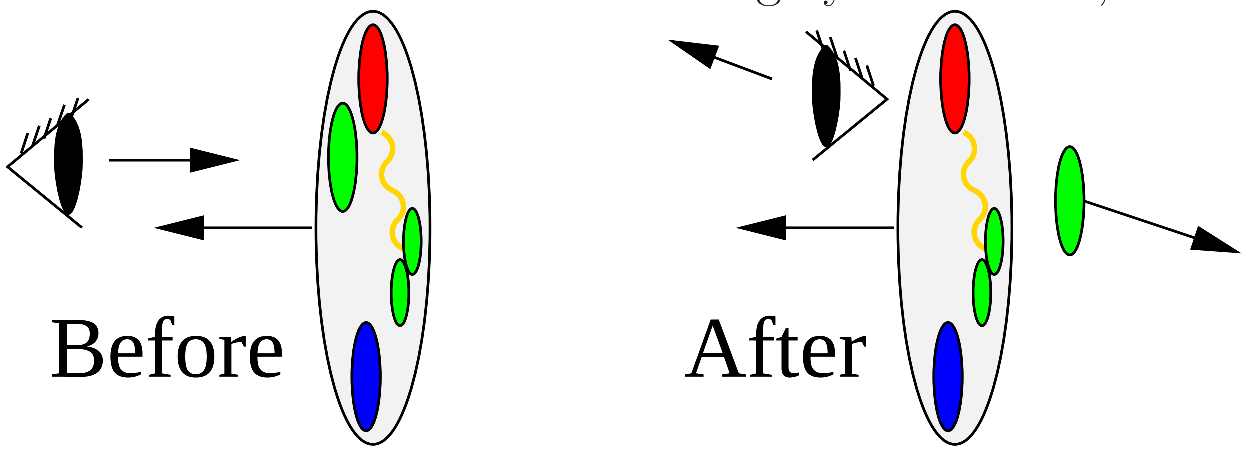
High Q^2



Valence Quarks and QCD at work

What Does DIS Probe?

In a frame where the nucleon is highly relativistic,



Nucleon is

Flat from length contraction

Probe interacts once

Frozen from time dilation

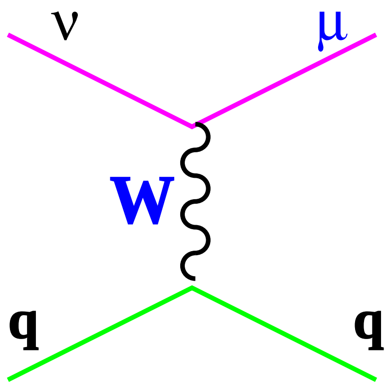
Quark is carrying a fixed fraction of nucleon momentum, x

Neutrinos interact weakly with quarks (not gluons)
So, νN DIS is like taking a "snapshot" of the quarks in the nucleon

So by taking the ensemble of all snapshots…

… can we reconstruct the movie?

νN DIS is measured by counting charged-current interactions:



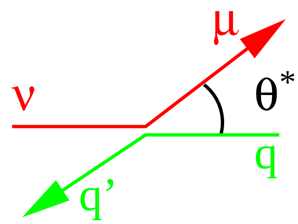
Reconstruct: muon angle,
muon momentum
and total energy

$$Q^2 = 4E_\nu E_\mu \sin^2(\theta_\mu/2) = \text{4-momentum transfer}$$

$$x = Q^2/2M(E_\nu - E_\mu) = \text{quark fractional momentum}$$

$$y = 1 - E_\mu/E_\nu = \text{inelasticity}$$

Charged-Current Weak Interaction selects spin states:



Interaction	Total Spin	$\frac{d\sigma}{dy}$	
ν-q: or $\overline{\nu}$-$\overline{q}$	0	1	
$\overline{\nu}$-q: or ν-$\overline{q}$	1	$(1-y)^2$	$2(1-y) = 1 + \cos^2\theta^*$

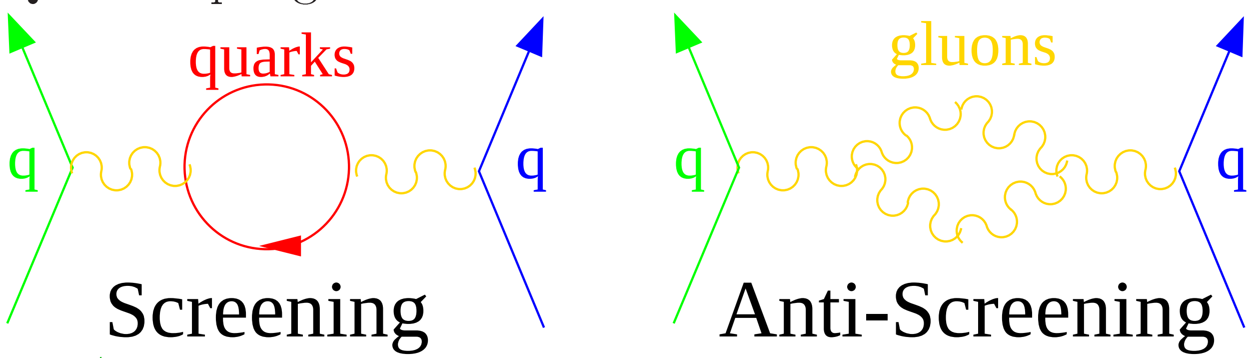
Can use y information to find numbers of quarks and anti-quarks with a given x for each Q^2.

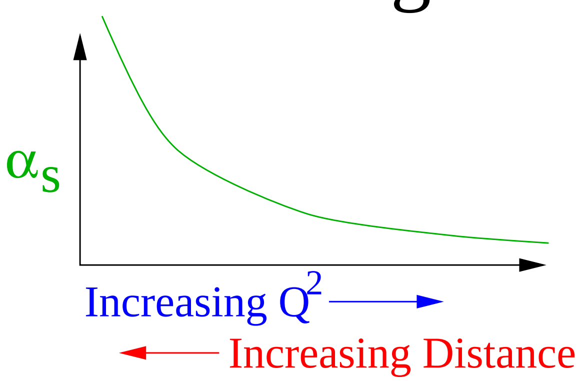
QCD has some "interesting" properties...

- QCD coupling is denoted by α_s
- QCD is a non-Abelian gauge theory $\Rightarrow$

3-Gluon Vertex

- QCD coupling "runs" with scale of interaction





$$\alpha_s(Q^2) \propto \frac{1}{\log Q^2/\Lambda^2} + \cdots$$

Anti-Screening Dominates!

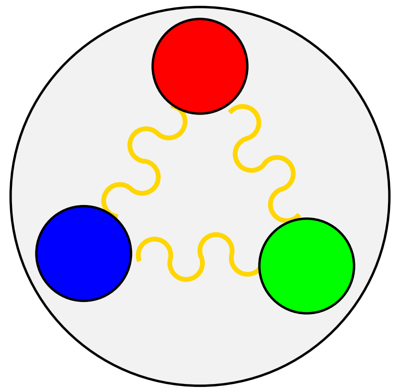
- QCD is "asymptotically free" at small distances (high Q^2), and strong at large distances (low Q^2)

  $\Rightarrow$ No free quarks!

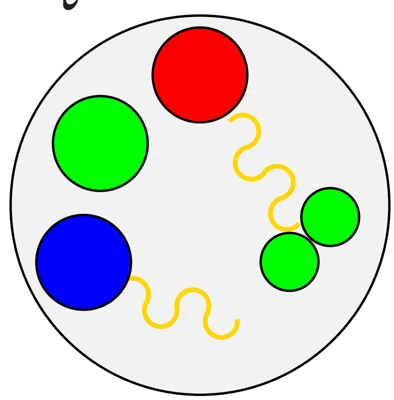
  $\Rightarrow$ QCD is "weak" inside proton... pQCD!

What Does QCD Do for Deeply-Inelastic Scattering?

pQCD cannot predict momentum distributions of quarks...



... but it can predict how they would change with Q^2

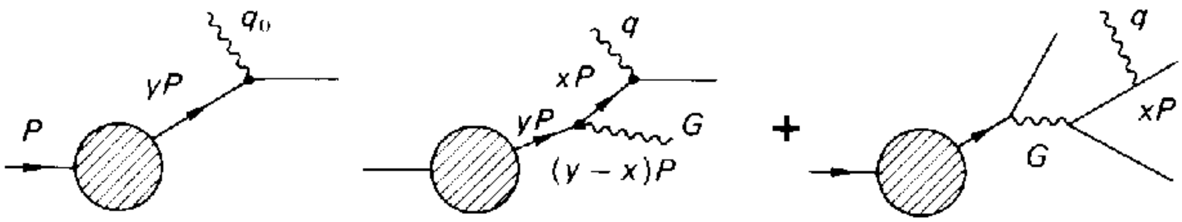


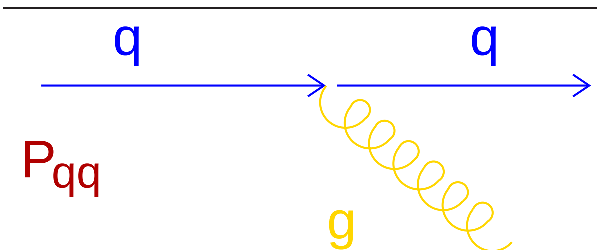
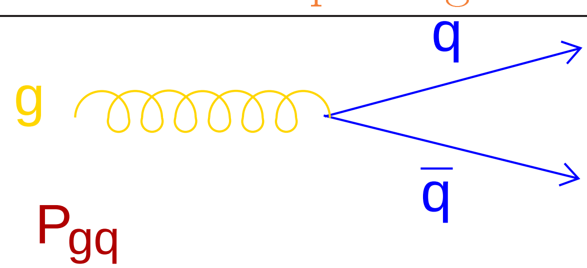
If QCD does describe proton dynamics...

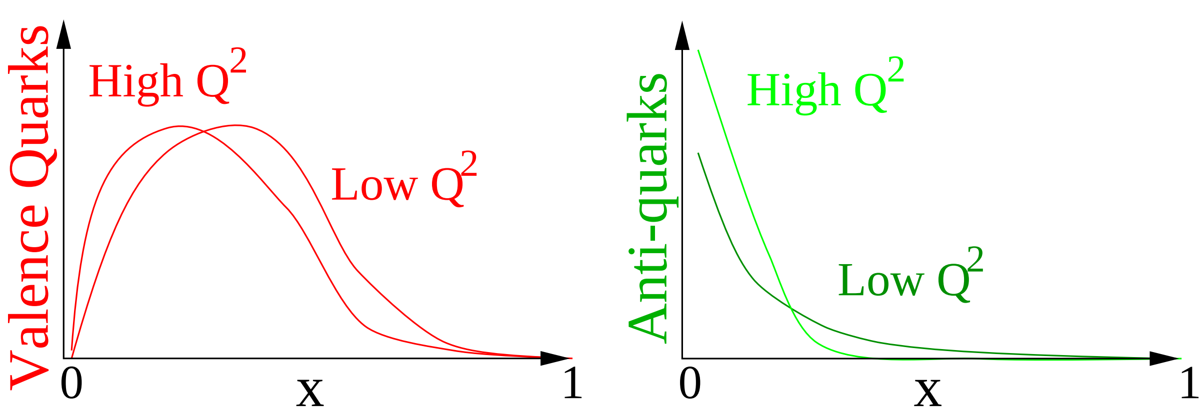
(the movie of the proton)

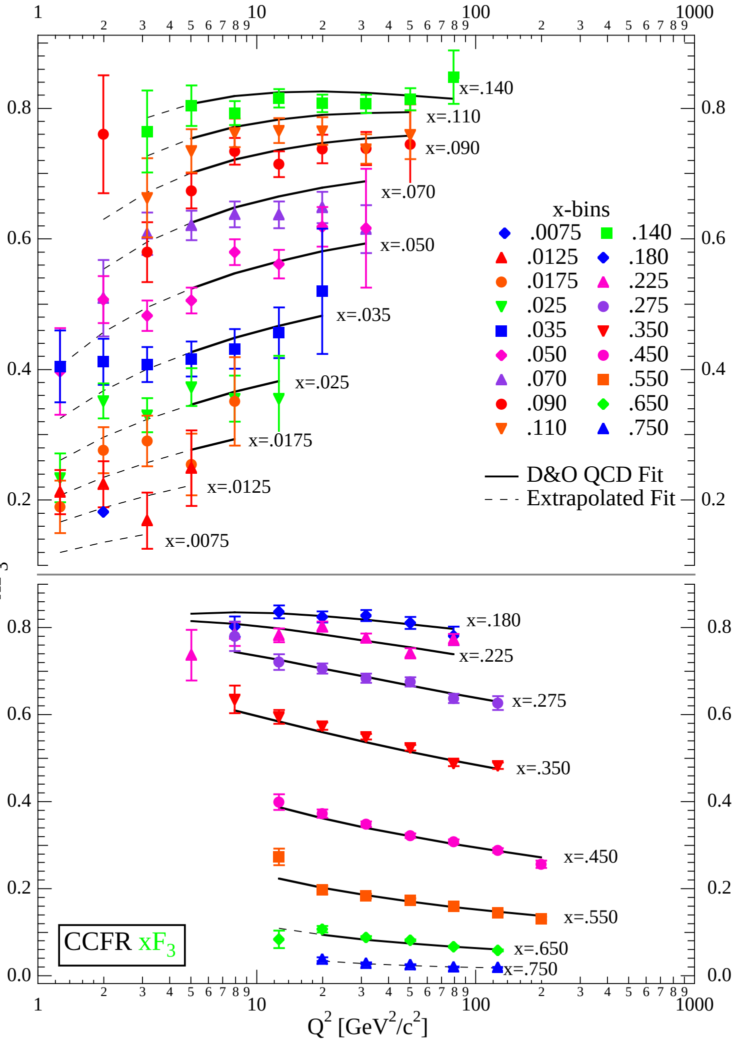
...then scale (Q^2) *effects are our movie review*

Two QCD Processes which modify the Structure Functions of Deeply-Inelastic Scattering



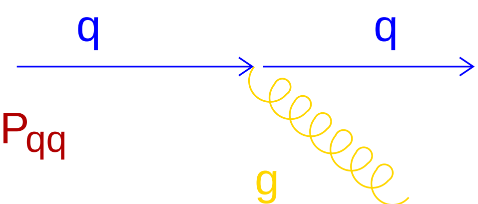
Quark Bremsstrahlung	Gluon Splitting
	
Quarks carry less momentum Affects all quarks	Makes quark-antiquark pairs at low momentum No change in valence quarks

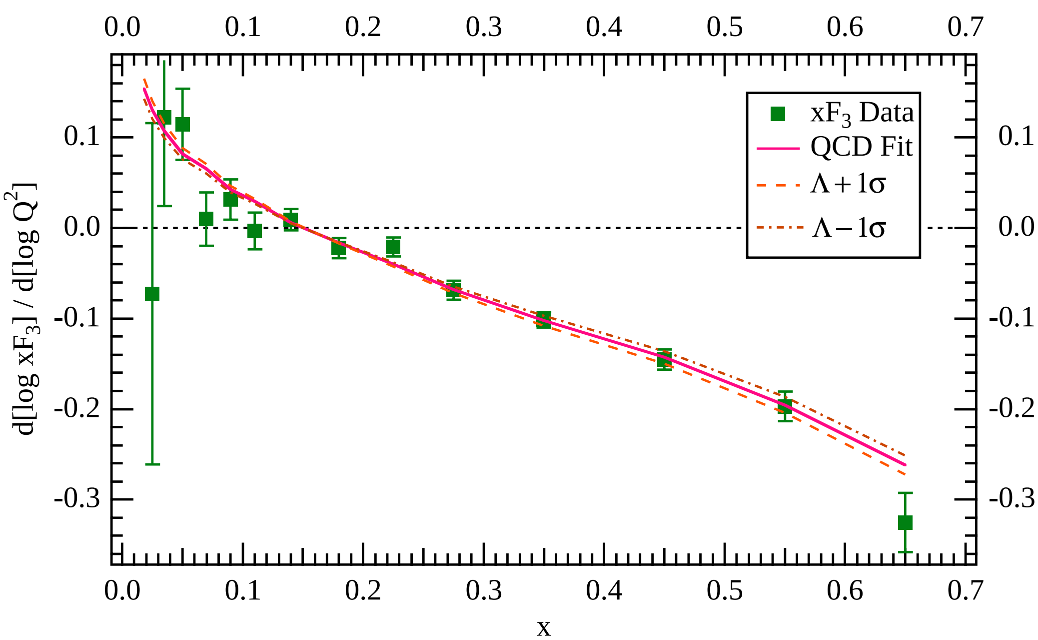




Valence Quark Distribution

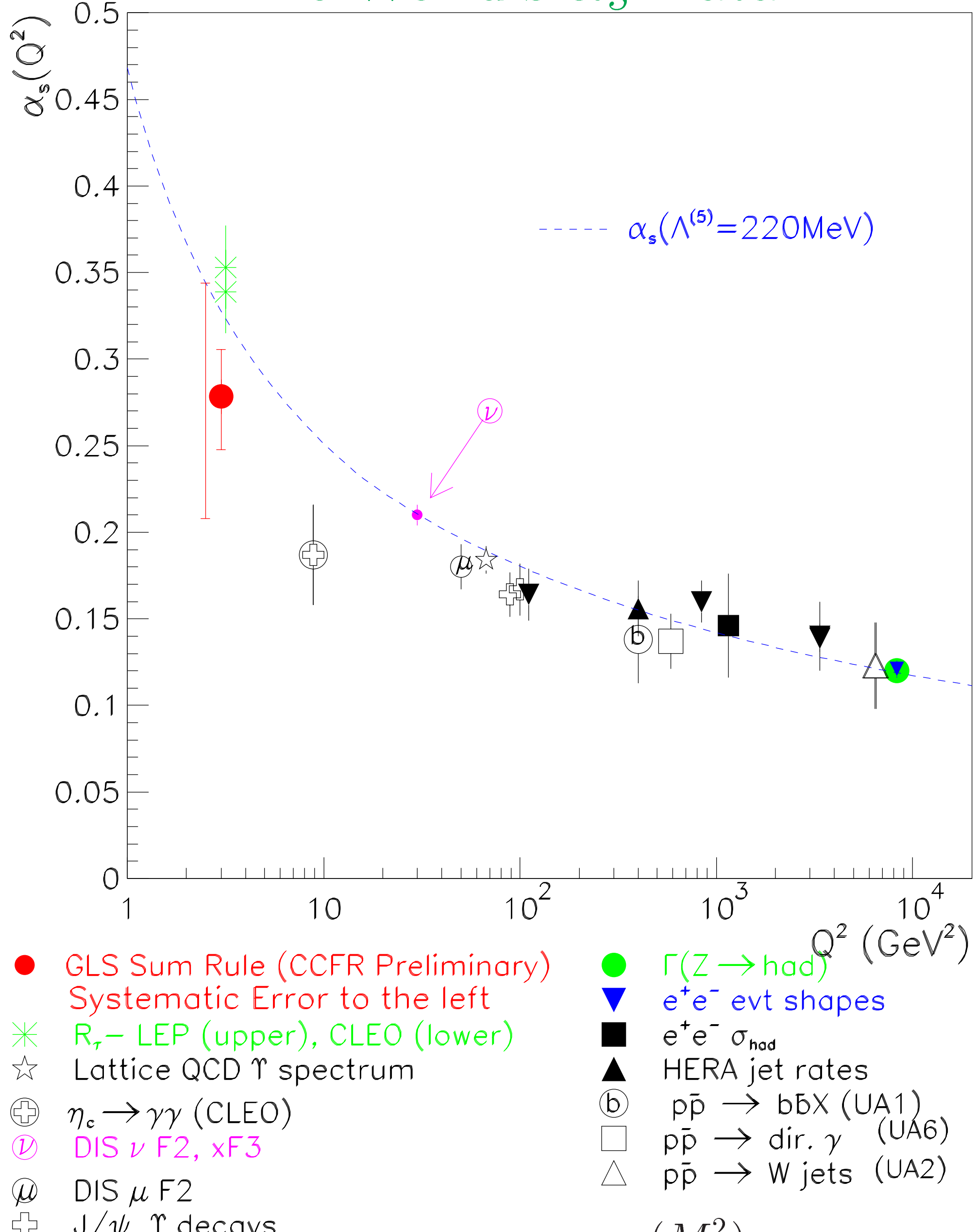
$$\frac{dF_3}{d\log Q^2} = \frac{\alpha_s(Q^2)}{\pi} \times \int_x^1 P_{qq}\left(\frac{x}{z}, Q^2\right) F_3(z, Q^2)dz$$





(W.G. Seligman *et al.*, `hep-ex/9701017`, to appear in Phys. Rev. Lett.)

The World's α_s Data



	$\alpha_s(M_Z^2)$
CCFR Non-Singlet Evolution	$0.119 \pm 0.0025 \pm 0.004$
CCFR GLS Sum Rule	$0.112 \pm .010 \pm .005$

(J. Yu *et al.*, Moriond '97)

Impressive verification of QCD over

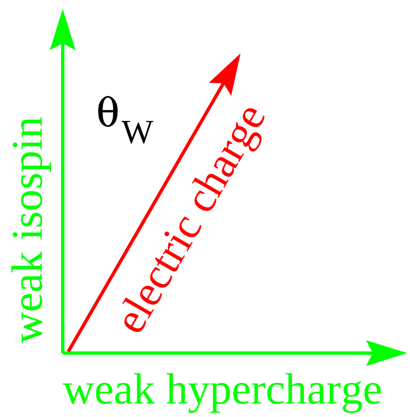
$$1 < Q^2 < 10^4 \text{ GeV}^2$$

Electroweak Unification and νN DIS

Unification of Weak and Electromagnetic Forces

$$\begin{array}{ccc} \text{Weak} & & \text{Electromagnetic} \\ \downarrow & & \downarrow \\ W^\pm,\, Z^0 & & \gamma \end{array}$$

Want to make a single high-energy theory



Weak Isospin set by $W^\pm$ coupling, G_F

Electric charge set by $\alpha_{\rm em}$

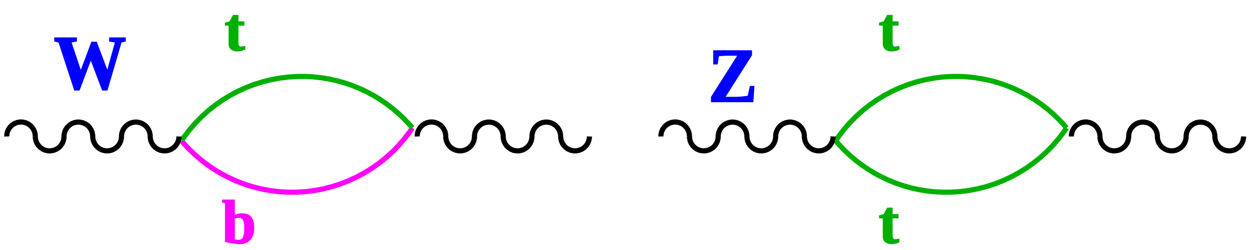
Z^0 properties set by θ_W

- G_F, known to 20 ppm
- $\alpha_{\rm em}$,known to 45 ppb
  (but only to 700 ppm at $Q^2 \sim M_Z^2$)
- Single "High Energy" Parameter: M_Z, known to 24 ppm
  - But $\sin^2\theta_W$ or M_W could also be used...

OK, that's it! So why am I telling you this?

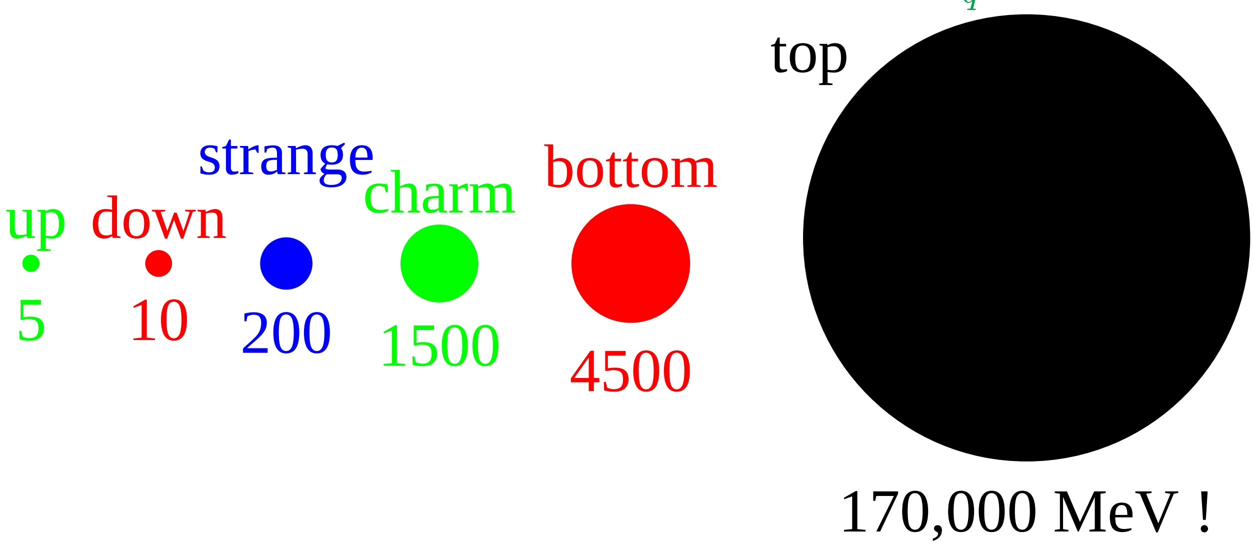
Because there are complications!

Processes like...



... will affect measurements!
(even at low energy, $Q^2 << m_t^2$)

These diagrams involving quark loops have an effect on weak interactions that is proportional to m_q^2



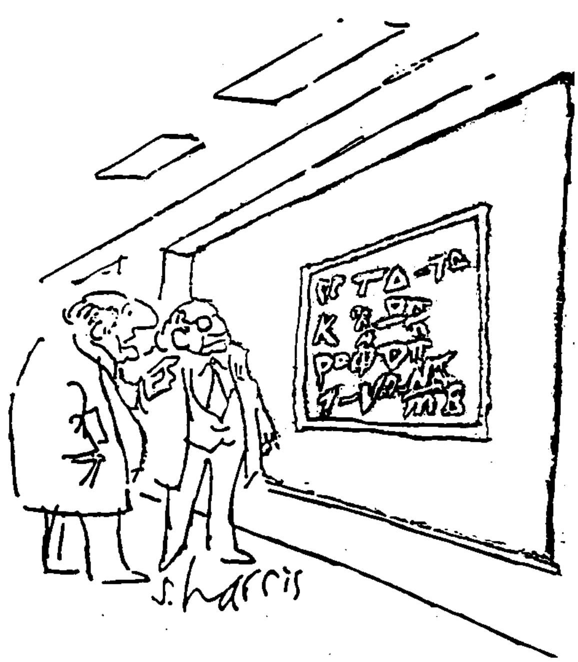
- The large effect from large **top quark** mass allowed its mass to be "measured" *before* it was ever observed
- Similarly, the as yet undiscovered Higgs boson can be "weighed" (an effect $\propto \log m_{\text{Higgs}}/m_Z$)
- But an unexpected heavy particle or other new physics could have a large effect also...

The Electroweak Standard Model is Tested to Highest Precision in...

- Z^0 Bosons from e^+e^- collisions at LEP and SLC
  - m_Z, Γ_Z, asymmetries in Z^0 decay
- $W^\pm$ Bosons in $p\overline{p}$ collisions at Tevatron, LEP II
  - m_W, Γ_W
- ν-Nucleon Deeply Inelastic Scattering! (FNAL, CERN)
- Atomic Parity Violation

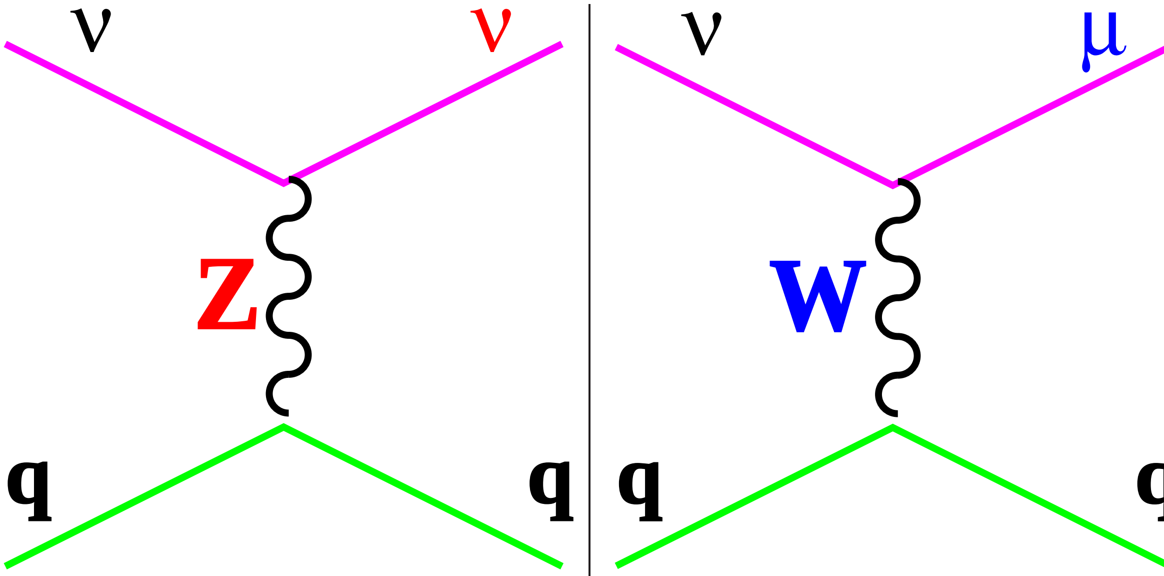
Why test in so many processes?

1. Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory
2. Measurements probe loop corrections from heavy particles differently
3. May find new physics in unexpected discrepancies



"Putting a box around it, I'm afraid, does not make it a unified theory."

How Does $\nu - N$ DIS Measure $\sin^2\theta_W$?



Neutral-Current
$\mathcal{F}(\sin^2\theta_W)$

Charged-Current
1

Fraction of neutrino interactions producing a muon is related to $\sin^2\theta_W$.

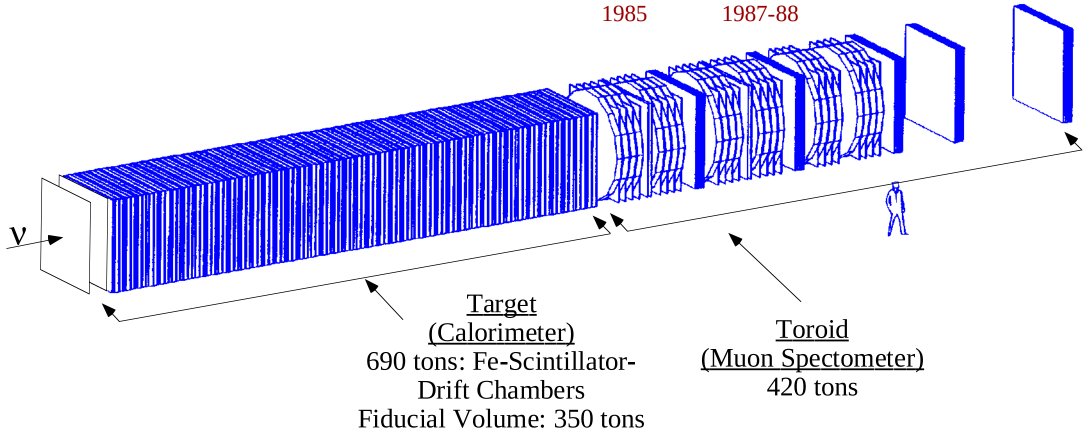
To measure $\sin^2\theta_W$ *in* νN *DIS…*

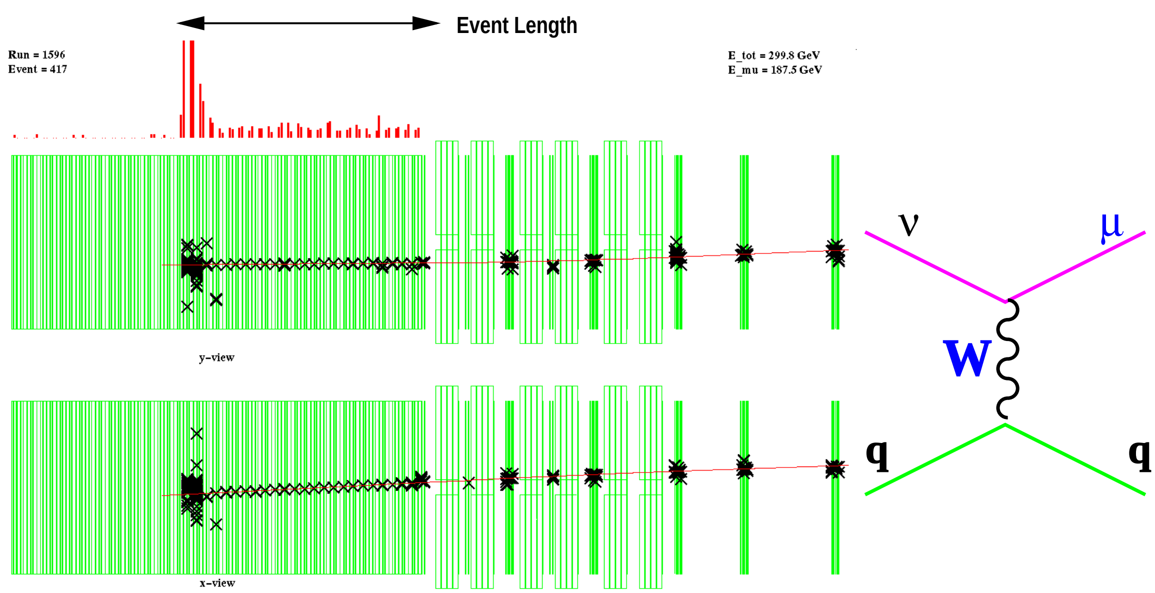
…need to identify only muons

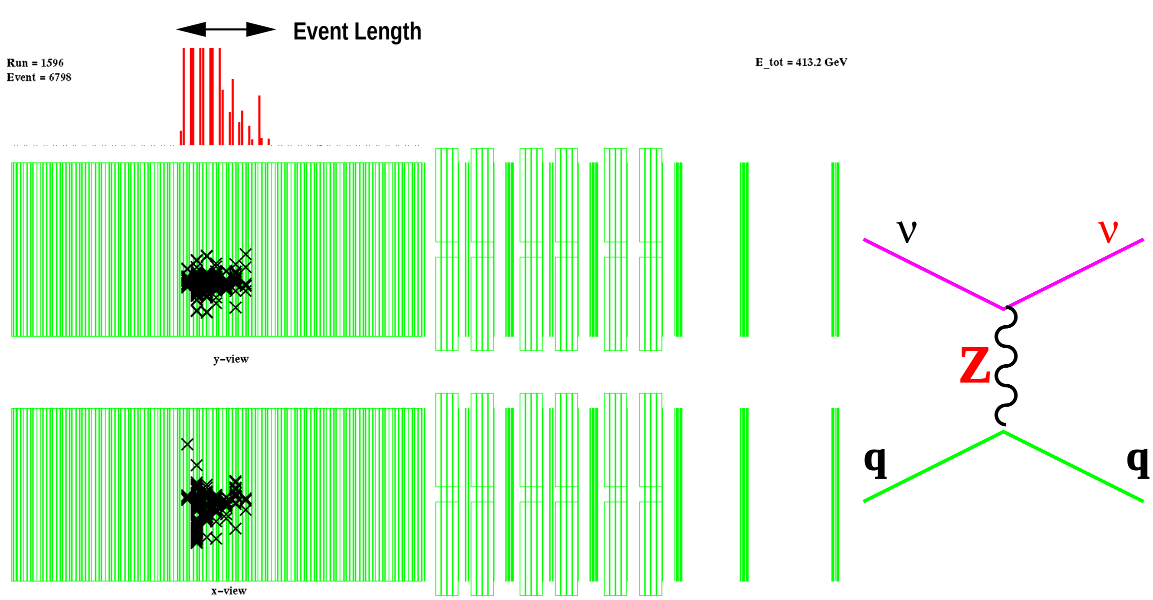
CCFR (Columbia-Chicago-Fermilab-Rochester)

LAB-E Detector - Fermilab E744 and E770

1985 1987-88





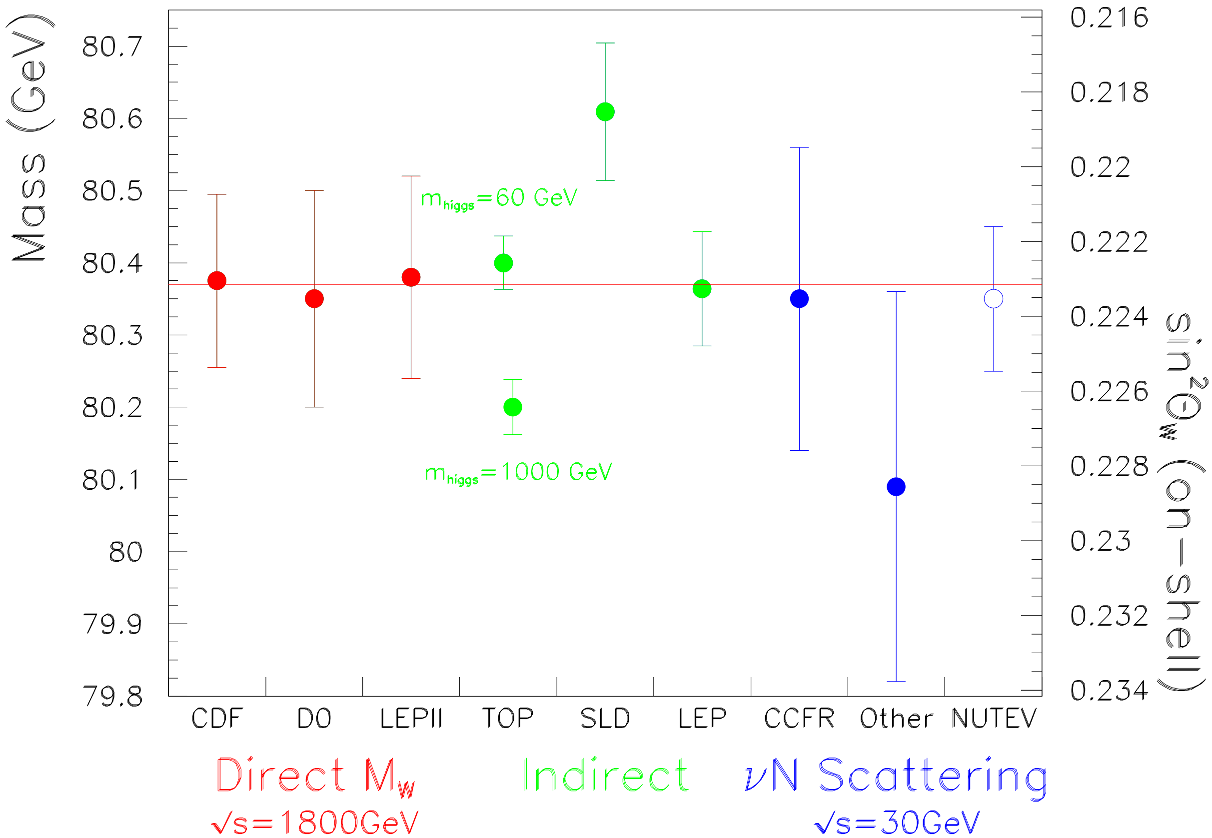


Results from CCFR Experiment

New CCFR Preliminary $\sin^2\theta_W = 0.2236 \pm 0.0041$

(K.S. McFarland *et al.*, submitted to Phys. Rev. **D**)

Convert CCFR and other results to M_W and compare



- Excellent agreement in a wide variety of measurements
- No evidence for new physics
- Upcoming experiments will improve these measurements
  - Current FNAL Experiment NuTeV will improve νN error by a factor of 2

Search for Neutrino Oscillations

Charged-Current Weak Interactions ($W^{\pm}$) of quarks,

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

can change quarks from one doublet to another.

But Weak Interactions of leptons can't!

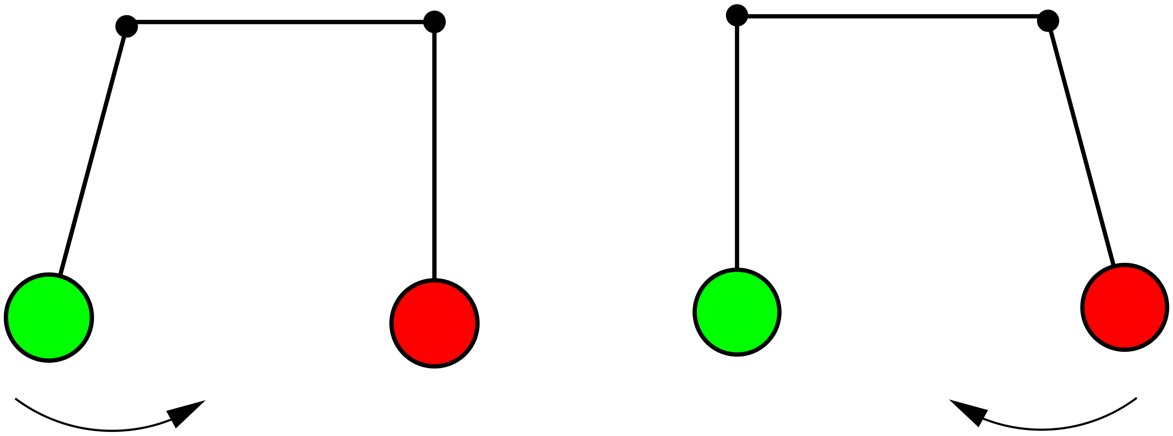
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Why Not?

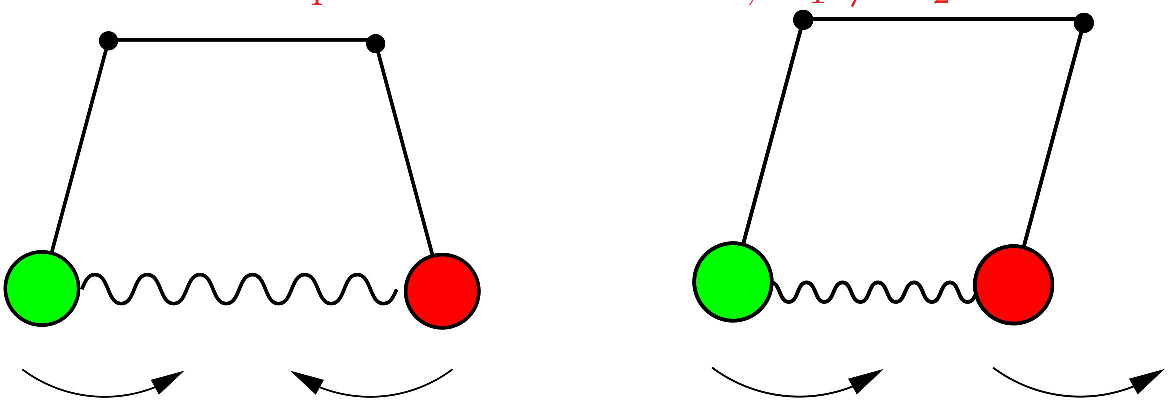
If there were an interaction which coupled between doublets in the lepton sector...
...Neutrino Flavor Oscillations could be an observable consequence.

Analogy: Coupled Pendula

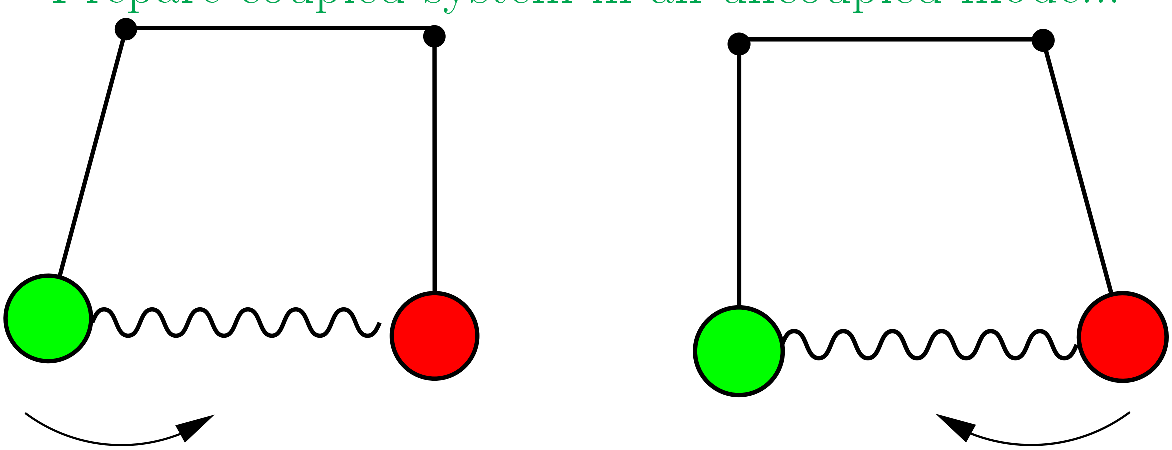
Uncoupled Normal Modes



Coupled Normal Modes, $\omega_1 \neq \omega_2$



Prepare coupled system in an uncoupled mode...



...and it oscillates

Neutrino oscillations require:

1. Unequal (non-zero!) neutrino masses, Δm^2
2. Mixing of flavors in a single mass state, α

Transition probability from an initially pure flavor state:

$$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\alpha_{12} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

Δm^2 is the $(m_a^2 - m_b^2)$ for the two mass eigenstates in eV^2

E is the neutrino energy in GeV, and

L is the length between the point of creation and the point of detection in km.

CCFR QT ν Beam at Fermilab creates ν_μ from $\pi, K \rightarrow \mu\nu_\mu$ decays.

- Pure flavor state at point of creation
- $< E > \sim 100$ GeV, $L \sim 1$ km
- Most sensitive at $\Delta m^2 \sim 100\ \mathrm{eV}^2$
- Typical for accelerator experiments...

Why Expect to Find ν Oscillations?

1. Cosmology would like massive dark matter to close the universe ($\Sigma\, m_\nu \sim 50$ eV)
2. *ONE* accelerator experiment, LSND, has shown evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations ($\Delta m^2 \gtrsim 10^{-1}$ eV^2)
   Consensus of field: contradicts other experiments(?), needs verification (!)
3. Ratio of ν_e to ν_μ in neutrinos from cosmic ray showers in atmosphere is too high ($\Delta m^2 \sim 10^{-2}$ eV^2)
4. Fewer solar neutrinos seen than predicted ($\Delta m^2 \sim 10^{-5}$ eV^2)

The first of these ranges of Δm^2 has been probed by *many* accelerator experiments...

...but to look at low Δm^2 requires a long neutrino beam!

(oscillation probability $\propto \frac{L\Delta m^2}{E}$)

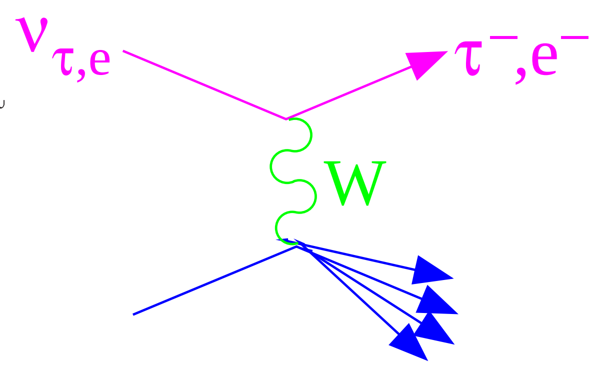
Long-baseline ν Beam

small ν flux

truly *massive* detector needed for rate

Accelerator-based ν oscillation experiments usually look for appearance in a fine-grained detector

Search for τ, e appearance in a ν_μ beam



Too much \$\$\$ to buy a detector capable of...

- observing τ, which decays quickly $(\sim 10^{-13}$ sec$)$
- observing e, which quickly loses energy
- only μ, which can penetrate material easily and is long-lived, can be found inside hadronic shower

$\boxed{\text{CCFR Technique}}$

- Count fraction of events with an observed μ
- Interactions of ν_τ and ν_e will rarely produce muons
- **Muon Neutrino oscillations will** *lower* **fraction of events with a** μ

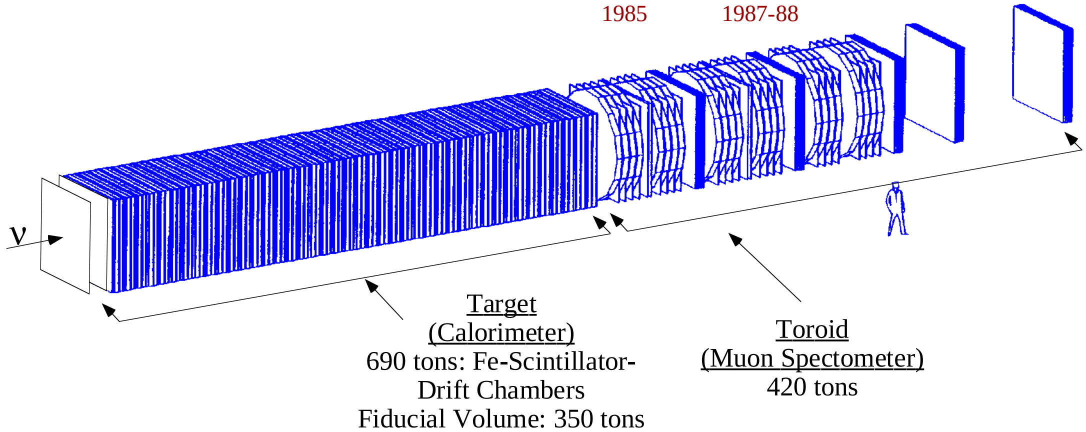
Can infer neutrino oscillations...

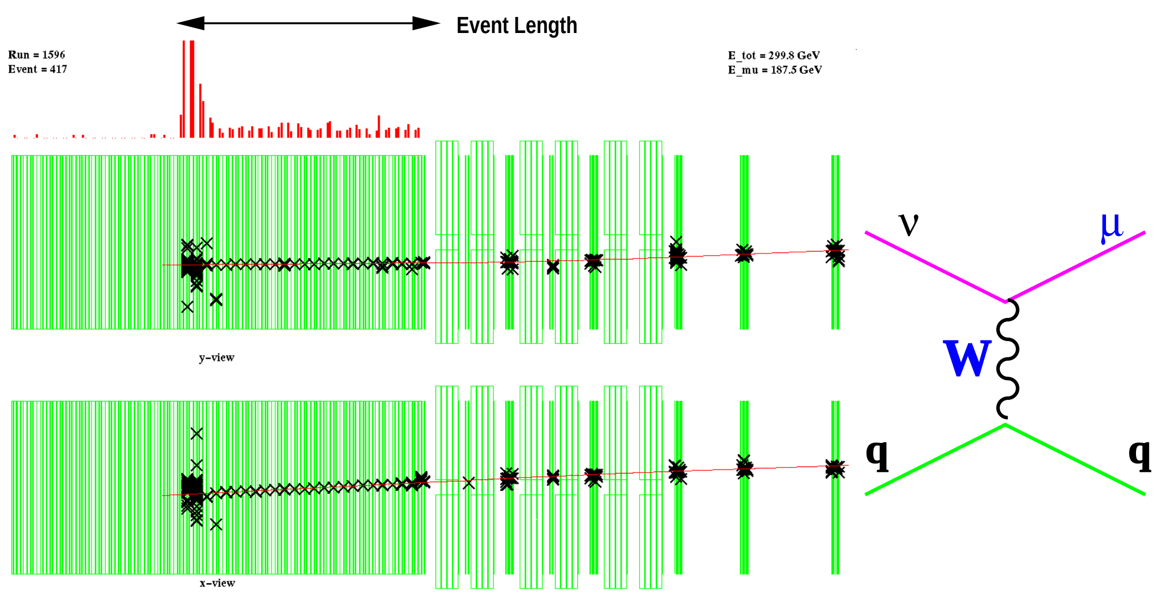
... by only identifying one type of lepton!

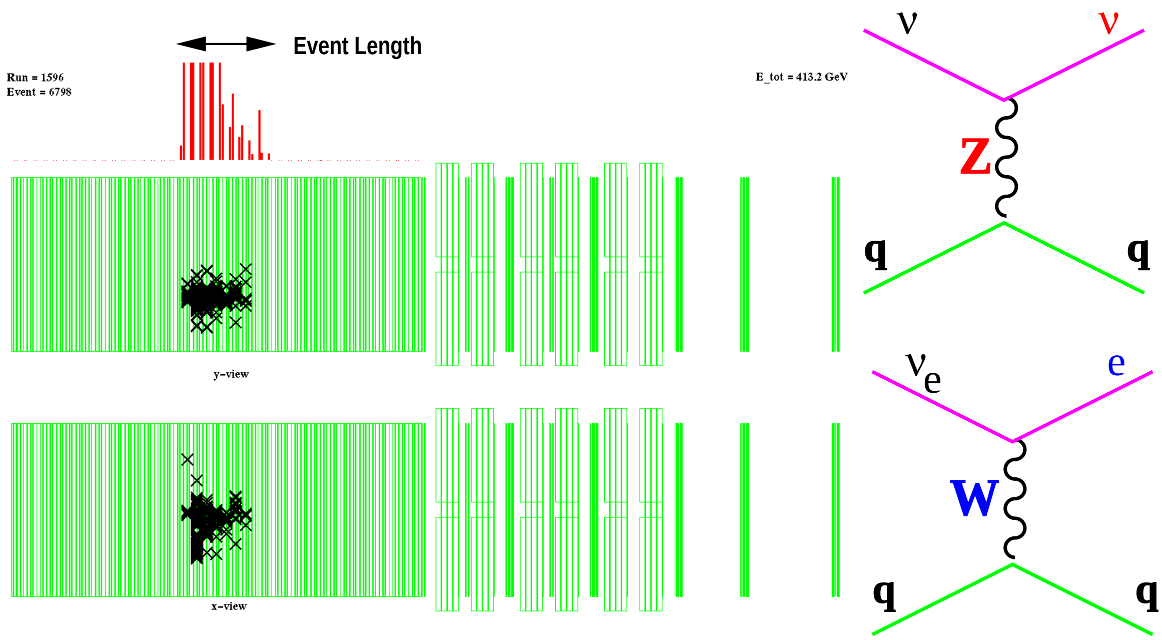
CCFR (Columbia-Chicago-Fermilab-Rochester)

LAB-E Detector - Fermilab E744 and E770

1985 1987-88



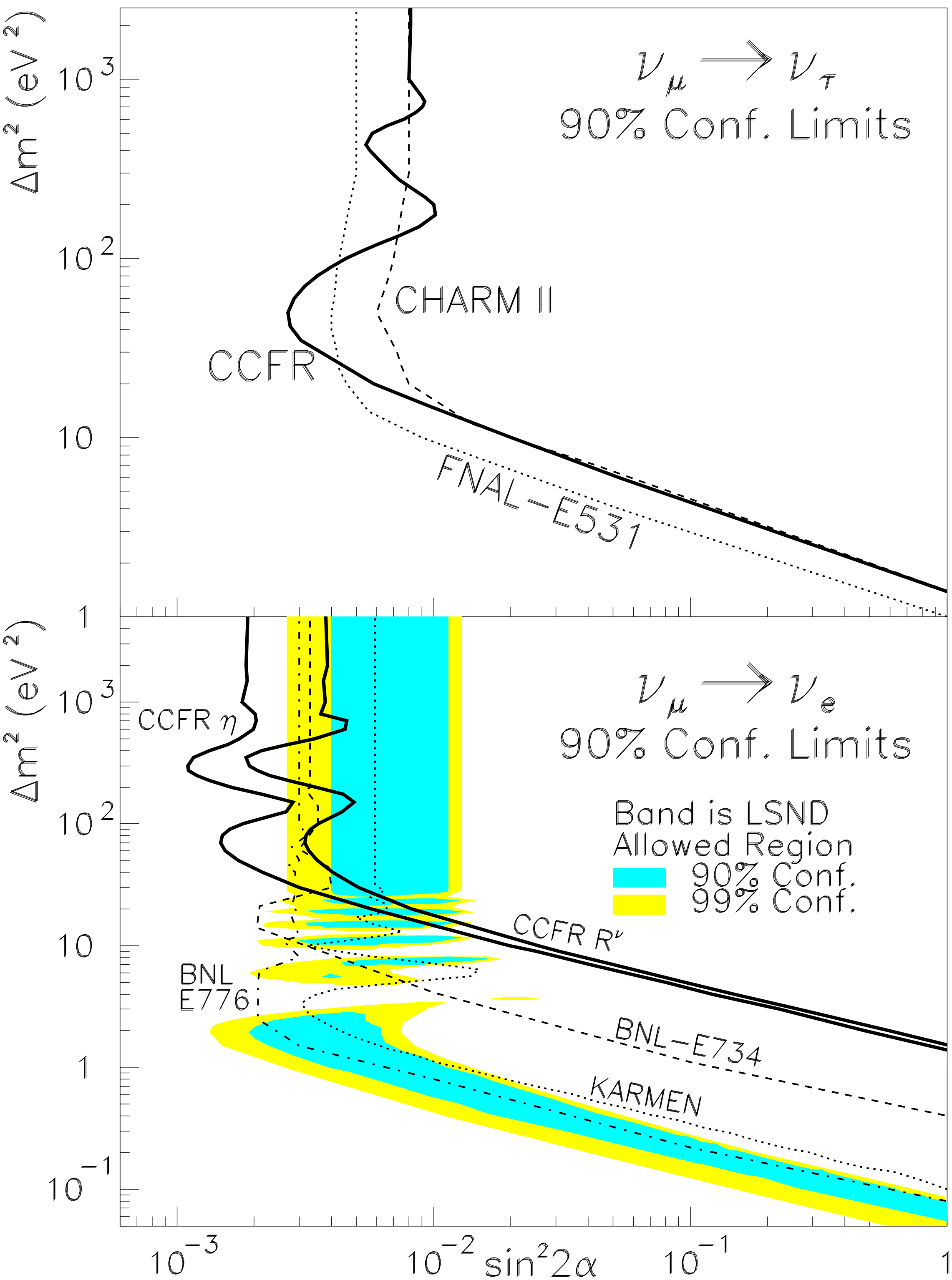




CCFR Data agrees with expectation
⇒ Limits on Oscillations

(K.S. McFarland *et al.*, Phys. Rev. Lett. **75**, 3993

A. Romosan *et al.*, Phys. Rev. Lett. **78**, 2912)



The MINOS Experiment

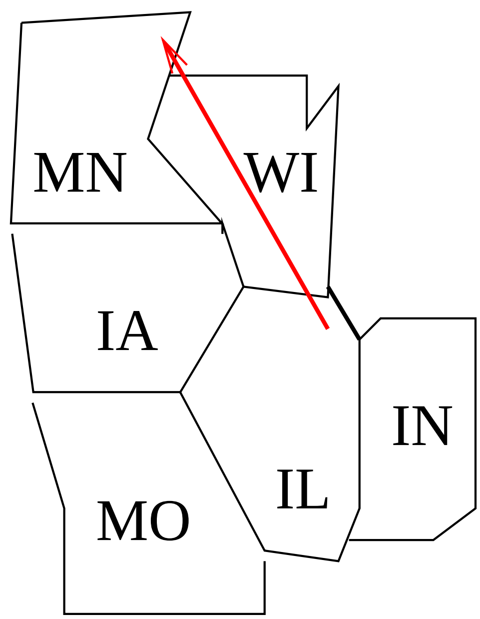
One ν Beam, two large coarse-grained massive detectors, each similar to CCFR detector:

NEAR: $\approx 1km$ from proton target

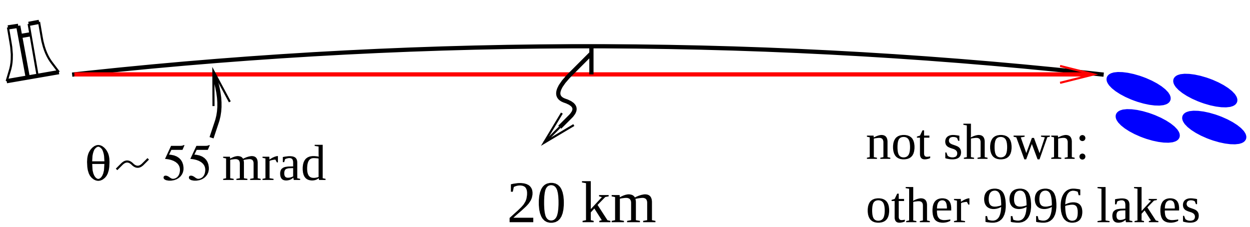
FAR: $730km$ from proton target in the
Soudan Mine in Minnesota
Only 3 events/ton/year
$\Rightarrow$ 10 Kton detector

The ν beamline

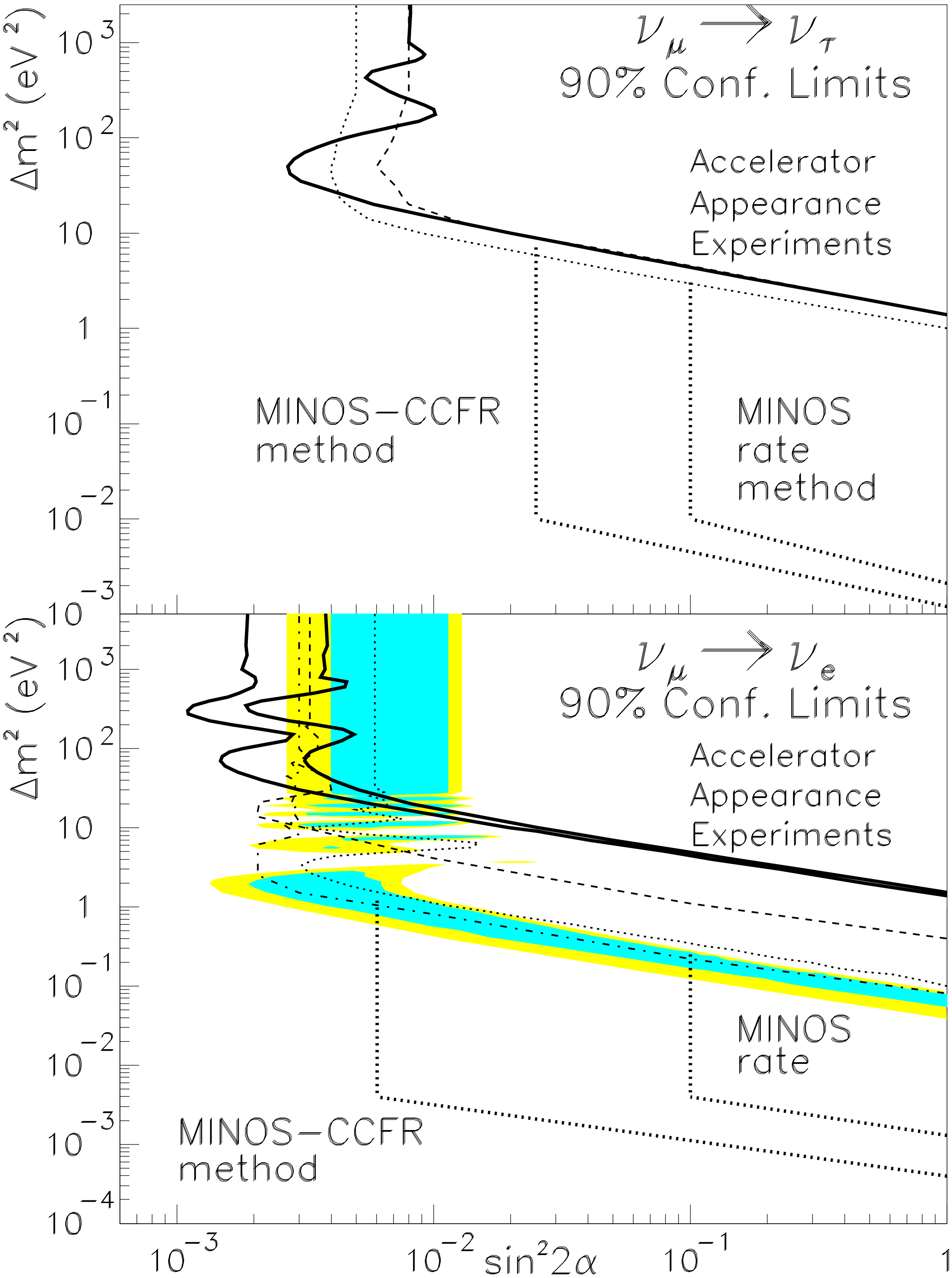
View From Above:



Side View:

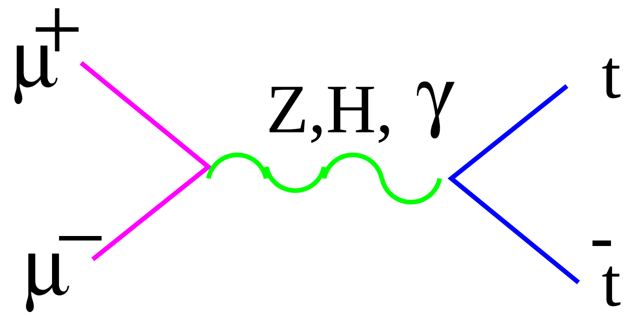


MINOS Sensitivity for two years of Running:



The FAR Future

$$? \begin{array}{l} \nearrow \text{Very Large Hadron Collider}, \sim 40\ \text{TeV}\times 40\ \text{TeV}\ pp \\ \rightarrow \text{Next Linear Collider}, \sim 1\ \text{TeV}\times 1\ \text{TeV}\ e^+e^- \\ \searrow \text{First Muon Collider}, \sim 2\ \text{TeV}\times 2\ \text{TeV}\ \mu^+\mu^- \end{array}$$



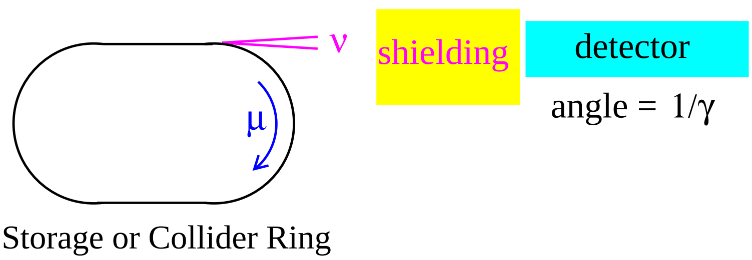
Why a Muon Collider?

- e^+e^-, $\mu^+\mu^-$ collisions can transfer full $\sqrt{s}$ to the final state
- As in proton colliders, muon collider storage rings possible at these energies ($m_p > m_\mu \gg m_e$)
  (at TeV energies, e^+e^- only possible in single pass linear collider)

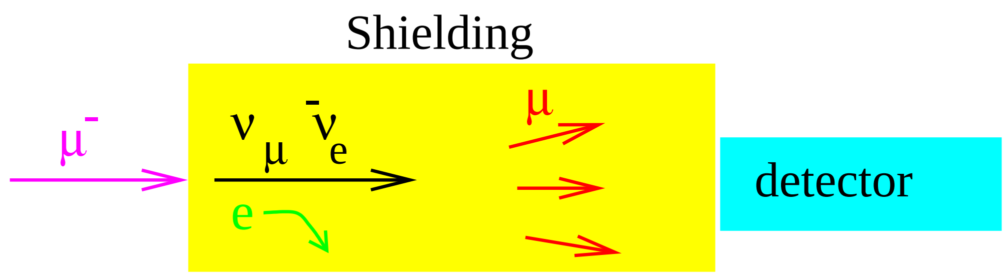
Complication: $\tau_\mu \approx 2\mu$ sec

- Extremely bright muon source needed;
  Acceleration must occur quickly
- $\mu \rightarrow e\nu\nu$
  - Final state electrons heat/irradiate magnets, shower in collider detector.
  - ν. . . make a beam!

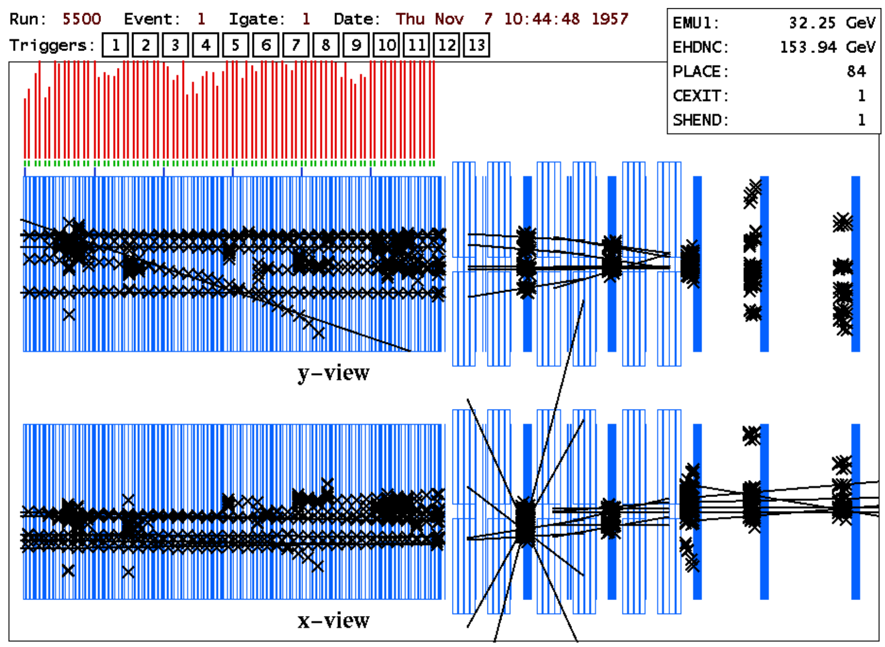
ν Beams at a μ Collider



- Well-collimated ν beam, simple production
- Extremely high rates (10^3 times MINOS beam)
  (ν beam can be a *radiation* hazard!)



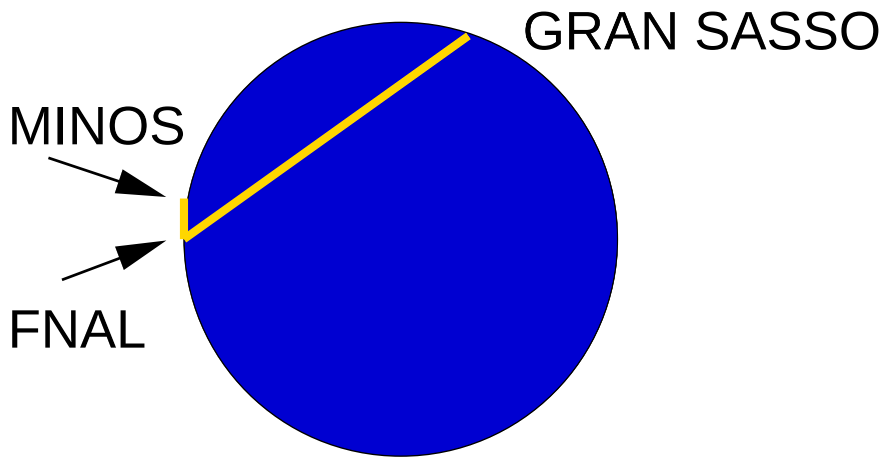
CCFR/NuTeV: 600 m downstream of Linear Accelerator



Not necessarily the best experiment...

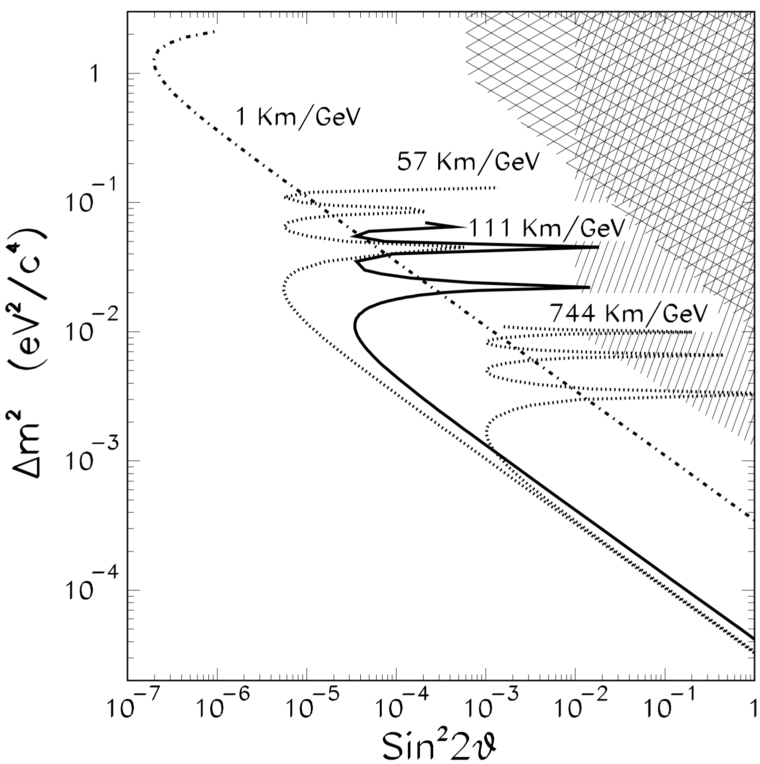
Very Long Baseline ν Oscillations

To the ends of the earth?

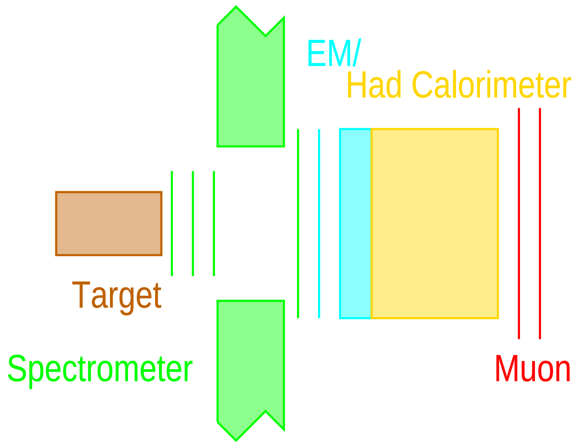


E_μ (GeV)	L (km)	M_{detector} (KTon)	$\nu_e N \to e^- X$/year
1.5	1	1	5×10^6
20	732	10	2×10^5
20	9990	10	1×10^3

(S. Geer, hep-ph/9712290)



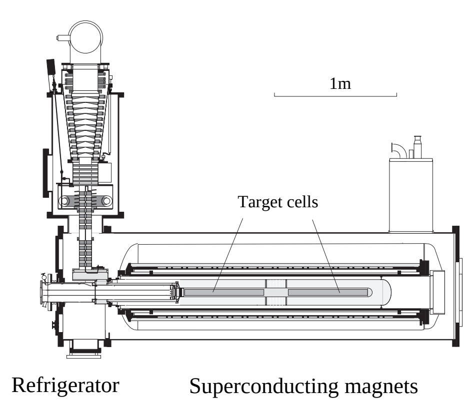
Small Targets? In a ν Experiment?



How is this possible?

Even a parasitic experiment at a 250 GeV muon collider would get a few$\times 10^5$ ν interactions/yr in a g/cm^2 target!

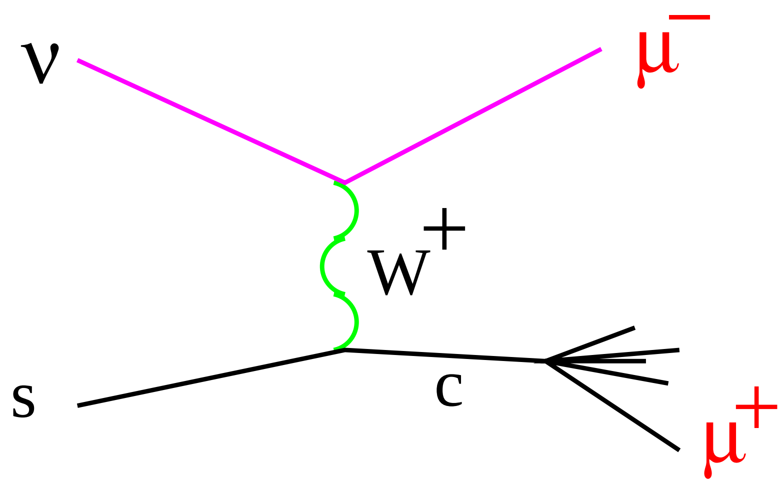
- Light Nuclear Targets: Do quarks know they're inside a heavy/light nucleus?
- H_2 vs D_2: Is $u(x)$ in proton $= d(x)$ in the neutron
- Polarized Nuclear Targets: Do Sea Quarks know the spin of the nucleus?



Solid Butanol $(CH_3(CH_2)_3OH)$ target (SMC)

Why use ν's on Light Targets?

- Charged Lepton Scattering has looked at Nuclear Dependences, but only ν scattering gives you clean up and down separation ($\cos\theta^*$ distributions)
- $\sigma^{\nu} \pm \sigma^{\overline{\nu}}$ gives valence and sea separation
- Extremely clean signal for scattering off of strange quarks- must be from the sea!



Conclusions

Neutrino Physics is Alive and Well at Fermilab!

CCFR/NuTeV experiments probe **three** fundamental forces

- Measurements of QCD
- Unification of Electromagnetic and Weak
- **NuTeV** (May 1996-September 1997) data soon!

Neutrino Oscillation searches underway

- CCFR/NuTeV search with *massive, coarse* detector at high Δ_m^2
- MINOS will pioneer long-baseline frontier

Muon Collider, future renaissance in neutrino physics?

- Orders of magnitude above current intensities will allow new capabilities in detectors
- Long-baseline neutrino oscillations to terrestrial limits?

Physics worth waiting for!